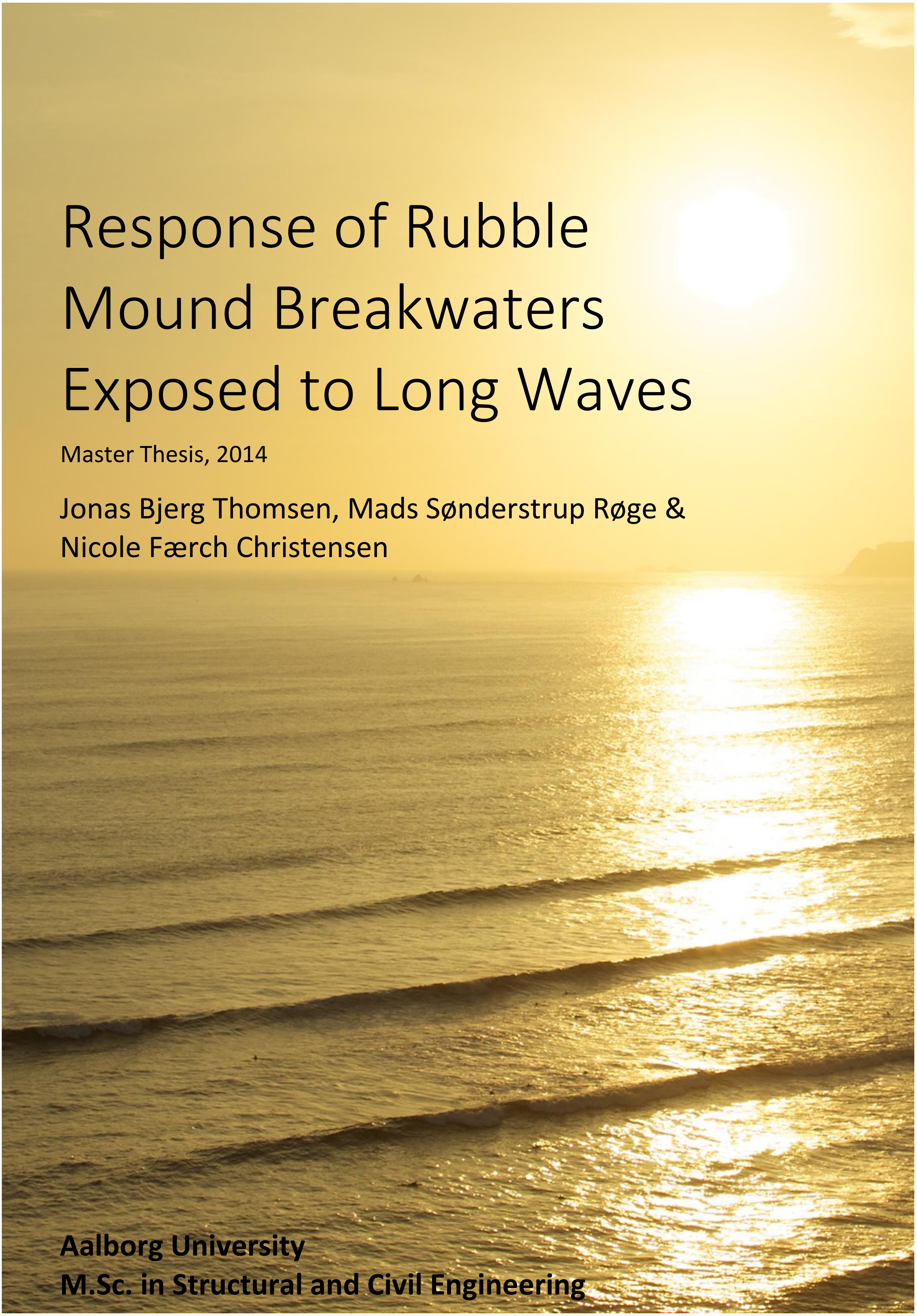

Response of Rubble Mound Breakwaters Exposed to Long Waves

Master Thesis, 2014

Jonas Bjerg Thomsen, Mads Sønderstrup Røge &
Nicole Færch Christensen

Aalborg University
M.Sc. in Structural and Civil Engineering

School of Engineering and Science
Aalborg University
Sohngaardsholmsvej 57
9000 Aalborg

Title: Response of Rubble Mound Breakwaters Exposed to Long Waves

Project period: September 2nd 2013 to June 10th 2014

Authors:

____
Jonas Bjerg Thomsen

____
Mads Sønderstrup Røge

____
Nicole Færch Christensen

Supervisors:

Thomas Lykke Andersen

Jørgen Quvang Harck Nørgaard

Completed: June 10th 2014

Preface

This thesis *Response of Rubble Mound Breakwaters Exposed to Long Waves* is the outcome of a master thesis within the period from September 2nd 2013 to June 10th 2014 at Department of Civil Engineering, Aalborg University. The thesis is made from a collection of three conference papers, presented at the 34th International Conference on Coastal Engineering (ICCE 2014) and one journal paper submitted to Coastal Engineering. The thesis presents the papers with an introduction of the subjects and an explanation of the necessity of treating the subjects.

Acknowledgements

The group behind this thesis would like to thank our supervisors Thomas Lykke Andersen and Jørgen Quvang Harck Nørgaard for their commitment in the project and co-operation during the studies. We would also like to thank Hans F. Burcharth and Jentsje W. van der Meer for their input with some of the papers. Finally, we would like to thank the technical staff in the laboratory for helping with the construction of our test set-up.

Summary in English

This master thesis *Response of Rubble Mound Breakwaters Exposed to Long Waves* treats the influence of long waves on different design parameters of rubble mound breakwaters. Various designs of breakwaters has been studied for decades, but because of the differences in wave climate, depending on location, and various requirements for performance, there is still a lack of design tools for several conditions. Through the years the focus have been on steep storm waves, which are often the design wave, and therefore the existing design tools are insufficient for long waves.

The thesis consists of four executive subjects, where different design formulae and their field of application are examined in relation to new model tests. The first subject is about stability of the armour in a conventional rubble mound breakwater where existing formulae appeared to be insufficient for the tested conditions with long waves. A new stability formula is presented based on the new model tests and adjusted to fit earlier stability tests.

The next subject treats the stability of berm breakwaters, where previous studies have shown a trend similar to the conventional rubble mound breakwater for short waves. The influence of long waves on the stability is studied by new model tests with different berm configurations, and a new design parameter is proposed to include in the previously mentioned new stability formula.

The third subject deals with overtopping on conventional and berm breakwaters. Existing methods to estimate the overtopping discharges are used and compared with results from new model tests, especially for long waves. Restrictions on the use of the existing methods are found, and a change is proposed to include the effect of long waves.

The fourth and final subject is about wave loads on a crown wall. Existing formulae are only validated for short waves and a permeable core, and therefore new model tests with long waves and different permeabilities are performed, and modifications to the existing formulae are suggested.

Dansk resume

Dette speciale *Respons af stenkastningsbølgebrydere udsat for lange bølger* omhandler indflydelsen af lange bølger på forskellige dimensiongivende parametre for stenkastnings-bølgebrydere. Forskellige udformninger af bølgebrydere er blevet undersøgt igennem årtier, men på grund af forskelligheden i bølgeklima afhængig af geografisk placering og forskellige specielle ønsker til udførelsen, er der stadig mangel på designredskaber for adskillige forhold. Der har igennem årene været fokus på stejle stormbølger, som ofte er dimensionsgivende, hvorfor de eksisterende designredskaber er mangelfulde ift. lange bølger.

Specialet består af fire overordnet emner, hvor forskellige designformler og deres anvendelse undersøges ift. nye modelforsøg. Det første emne omhandler stabilitet af dæksten i en traditionel stenkastningsbølgebryder, hvor eksisterende formler viste sig utilstrækkelige for de testede forhold med lange bølger. En ny stabilitetsformel er udviklet på baggrund af de nye modelforsøg og tilpasset til tidligere forsøg.

Næste emne omhandler stabilitet af banketbølgebrydere, hvor tidligere forsøg har vist en tendens tilsvarende en traditionel stenkastningsbølgebryder for korte bølger. Indflydelsen af lange bølger på stabiliteten er undersøgt ift. nye modelforsøg med forskellige banketkonfigurationer, og en ny designparameter er foreslået til inkludering i den tidligere nævnt stabilitetsformel for traditionelle stenkastningsbølgebrydere.

Tredje emne omhandler overskyl på traditionelle og banketbølgebrydere. De eksisterende metoder til estimering af overskylsmængder er anvendt og sammenlignet med resultater fra nye modelforsøg for specielt lange bølger. Anvendelsesbegrænsninger for de forskellige metoder er fundet, og en ændring er forslået til inkludering af effekten fra lange bølger.

Fjerde og sidste emne omhandler bølgelaster på en kronevæg. Eksisterende formler er kun valideret for korte bølger og en permeabel kerne, hvorfor nye modelforsøg med lange bølger og forskelige permeabiliteter er udført og modificeringer til eksisterende formler er forslået.

Contents

Appendices: Scientific Papers

List of Appended Papers

This master thesis consist of four papers enclosed as appendix and summarized in this thesis.

List of papers:

Paper 1 Thomsen, J.B., Røge, M.S., Christensen, N.F., Andersen, T.L. and Burcharth, H.F. (2014). *Rock Armour Stability in Shallow Water Waves Conditions of Low Steepness – A New Stability Formula.* In review in Coastal Engineering (Elsevier).

Paper 2 Thomsen, J.B., Røge, M.S., Christensen, N.F., Andersen, T.L. and van der Meer, J.W. (2014). *Stability of Hardly Reshaping Berm Breakwaters Exposed to Long Waves.* Proceedings of the 34th International Conference on Coastal Engineering, 2014, Seoul, Korea.

Paper 3 Christensen, N.F., Thomsen, J.B., Røge, M.S., Andersen, T.L., Burcharth, H.F. and Nørgaard, J.Q.H. (2014). *Overtopping on Rubble Mound Breakwaters for Low Steepness Waves in Deep and Depth Limited Conditions.* Proceedings of the 34th International Conference on Coastal Engineering, 2014, Seoul, Korea.

Paper 4 Røge, M.S., Christensen, N.F., Thomsen, J.B., Nørgaard, J.Q.H. and Andersen, T.L. (2014). *Wave Loads on Rubble Mound Breakwater Crown Walls in Long Waves.* Proceedings of the 34th International Conference on Coastal Engineering, 2014, Seoul, Korea.

Introduction to Thesis

Different types of waves are present at the sea, classified by their frequency and method at which they are generated. Most waves are generated as a result of energy transformation by surface shear between the wind and water surface. If the waves travel over a long distance they are classified as swells. These waves are not or only hardly affected by the local wind. Because of the long distance at which they travel, swells are often more sorted as waves with the same speed, group together.

Often swells have a much larger wave length and period (T < 40 sec.) than wind generated waves (T < 25 sec.). Because of the long wave period swells can pack a lot more energy, leading to different issues to solve when designing for protection against swells.

Figure 1: Example of swells.

Another type of long waves is tsunamis. These waves are often generated by underwater earthquakes, volcanic eruptions etc. In deep water, tsunamis have a much larger wave length than even swells, as the wave period can be between 5-60 min with a wave speed of up to 800 km/hr. In deep water the wave is therefore difficult to observe, but reaching more shallow water wave shoaling occurs, decreasing the speed of the wave and significantly increasing the wave height. The impact of these long waves is therefore considerable.

Rubble mound breakwaters are often used as protection against waves at harbours or to protect the shore against erosion. Many different topics have to be considered when designing the breakwater, in order to secure an optimal use. Three of these are:

- Stability of armour layer stones and berms.
- Overtopping discharges.
- Wave loads on superstructures.

Assessment of stability is important to ensure that failure of the breakwater do not occur. Therefore the necessary rock sizes must be determined. Different method are available when determining stability, but not many of these are validated for sea states with long waves as swells or tsunamis. By using the available methods, it cannot be guaranteed that the stability is correctly determined, hence failure might occur. The financial costs from this is significant, for what reason a comprehensive model test can be necessary. The financial cost and time consumption from this is though also significant. An effective tool for stability assessment is therefore needed.

Rubble mound breakwaters can both be constructed with and without a berm. For long waves the stability of a berm is also not covered completely, hence this is needed to be investigated.

The presence of a berm not only affects the stability but also the overtopping discharge. In harbour protection the amount of overtopping is limited in order to secure safe berthing of ships by minimizing disturbances inside the harbour. The amount of overtopping is often one of the design parameters for the level of the crest. Many different methods are available, giving very different results especially for long waves. An investigation of this difference and clarification of what method to use is therefore important in order to secure correct design of breakwaters.

In situations where the overtopping discharge is too high, further protection can be necessary. Here crown walls can be used. Presence of a crown wall though induces other issues, as this needs to be designed correctly. Different failure modes can occur, most of them because of wave loads. The existing tools for predicting these loads are mainly for short waves, leading to possible failure or oversizing of the structure when the sea state is dominated by long waves.

As stated in above the need of an investigation of existing design tools and suggestions of modifications is relevant for breakwaters in locations with long waves. This both reduces costs and time, and can prevent failure and large damage. The present thesis therefore investigates the three mentioned topics; stability of armour layer stones and berms, overtopping and wave loads on crown walls, in order to verify the usability of existing tools and propose new and improved methods. All investigations are based on a large amount of new model tests performed during the thesis, and the studies are shortly presented in the following sections.

Stability of Conventional Rubble Mound Breakwaters

Stability of conventional rubble mound breakwaters has been dealt with by several authors, but nowadays the most used design tool is the stability formulae by Van der Meer (1988). He found that the stability was highly affected by the breaking of the waves, leading to two stability formulae: One for plunging waves and one for surging waves. The formulae by Van der Meer (1988) were based on model tests mainly performed in deep-water conditions. Most rubble mound breakwaters are due to costs constructed in shallow-water conditions, where the Van der Meer (1988) formulae are not tested.

Van Gent (2003) continued the work by Van der Meer in order to include shallow-water conditions by making new model test for shallow-water conditions. From the tests he found a need of a modification of the formulae. Also a new stability formula was suggested.

The present thesis made use of 125 new model tests performed in a two-dimensional wave flume in order to continue the work on stability assessment. The tests mainly focussed on long waves and were used to evaluate the existing formula.

The test results showed a large uncertainty when using the prediction formulae, especially for the surging waves. Here much more damage was measured than the formulae predicted. This meant that using existing formulae leads to a significant overestimation of the stability (hence an underestimation of damage).

By analysing the new model test results, it was found that a new stability formula needed to be constructed, and thereby reducing uncertainties and improving the method of stability assessment. This work is presented in paper 1, where test set-up, tested condition and results are presented.

Stability of Hardly Reshaping Berm Breakwaters.

An effective way of reducing overtopping and costs during construction is by making berm breakwaters. This thesis continued the work by Lykke Andersen et al. (2012), which showed that the presence of a berm affected the wave breaking so that the stability always followed the plunging formula by Van der Meer (1988) also into the surging regime. Lykke Andersen et al. (2012) stated five reasons for the difference in the behaviour of stability of a berm breakwater and conventional breakwater. The present thesis investigated these reason in order to quantify when the stability follows the behaviour of a conventional breakwater and when it always follows the plunging formula. The investigation was based on 24 new model tests and 17 tests performed in a previous master thesis, with a range of different constructions. The tests showed an influence of berm elevation and width, both reducing the damage.

Furthermore a stability formula for berm breakwaters by Van Gent (2013) was investigated and tested outside its validated ranges. The test showed good agreement between the formula and test results, but the need of an upper limit for the formula was suggested, since the berm breakwater started to behave closer to a conventional breakwater.

Similar to stability of a conventional rubble mound breakwater it was found that when in shallow water the stability, when exposed to long waves, could not be predicted correctly by use of Van Gent (2003). The new suggested stability formula was therefore modified to also include a berm-factor, leading to a clear improvement of the damage prediction. The factor was though not calibrated to more than one front slope and only a limited range of wave steepnesses, berm elevations and berm widths.

The study of berm breakwater stability can be seen in paper 2.

Overtopping of Rubble Mound Breakwaters

The overtopping discharge on breakwaters have been analysed by several authors and the prediction methods provide a significant variation in the amount of overtopping especially for long waves. Therefore new model tests were performed in order to investigate this difference. The analysis can be seen in paper 3.

For conventional rubble mounds and berm breakwaters TAW (2002) has presented overtopping formulae, independent on the wave steepness for long waves, when reaching an upper limit. In the model tests a strong dependency on the wave period was found, and the formulae by TAW (2002) provided a significant underestimation for the long waves on the conventional breakwater. For that reason another roughness factor was proposed including the steepness of the waves when reaching the upper limit. When using this roughness factor in the upper limit, the scatter of the estimated overtopping discharges by use of TAW (2002) was reduced significantly and the overtopping for the long waves were no longer underestimated. For the berm breakwater Sigurdarson and Van der Meer (2013) proposed a roughness factor dependent on the wave conditions and the berm width to be used in the TAW (2002) formulae. This method provides a reliable estimate of the overtopping but with a lot of scatter.

Lykke Andersen (2006) proposed another prediction formula for berm breakwaters to determine the wave overtopping, which provided an overtopping discharge dependent on the wave period for all wave steepnesses. The formula provided a reliable estimate for the tests in shallow-water conditions, though an overestimation for all the tests in deep-water conditions. The reason for this was found to be, that the tested ranges for the deep-water tests were outside the validated area by the Lykke Andersen (2006) formula i.e. more narrow berm widths, higher berm elevations and lower wave steepnesses.

Another prediction method for determining the wave overtopping is the CLASH Neural Network (van Gent el al. (2007)), which is a database with more than 10,000 overtopping measurements including different geometrical and wave conditions for both conventional rubble mounds and berm breakwaters. The prediction method provides a reliable estimate for $q/\left(g\,H_{m0}^3\right)^{0.5} > 10^{-5}$ and does not provide any prediction for $q/\left(g\,H_{m0}^3\right)^{0.5} < 10^{-6}$. Furthermore, the method does not provide a prediction outside the validated ranges, which is why no prediction is given for some of the tested conditions and thereby the scatter decreases.

As the overtopping discharge often sets restrictions to the crest level, it is an important quantity to investigate. Overestimating the overtopping discharge and making an unnecessary high crest is costly due to a large amount of more material to be used. On the other hand an underestimation could also be very costly because of overtopping damaging buildings on the breakwater or the armour layer on the leeward side of the breakwater. Therefore, model tests are often performed to clarify the exact conditions at the location, but to limit the costs of model tests an initial state should be determined, which is why accurate prediction methods are necessary.

Loads on Crown Wall

Several authors have been dealing with prediction of loads on crown walls. Günbak and Ergin (1983) suggested a formula to predict the loads on a crown wall, by coupling the run-up height with the wave loads. Later Pedersen (1996) performed tests in deep- and intermediate-water conditions and adopted that the run-up height could be used to describe the loads. Nørgaard et al. (2013) modified the formula by Pedersen (1996) to include also shallow-water conditions based on new model tests. The modified formula was however only not evaluated for long waves.

In order investigate the influence of long waves on the reliability of the formula, new model tests were performed. The test were made for a permeable core and an impermeable core as the formulae by Nørgaard et al. (2013) were only verified for a permeable core. For tests outside the validation area higher load were measured than predicted. This means that when designing crown walls for sea states with long waves the crown wall would be underscaled and therefore failure could occur. Modifications and suggestions were presented for better estimations, but more tests are needed to include all ranges since only a small range was tested in the present thesis. In paper 4 the tested conditions and results can be seen.

References

Günback, A.R. and Ergin, A. 1983. Damage and repair of Antalya harbor breakwater. Proc. Conf. on Coastal Structures, Alexandria, Egypt.

Lykke Andersen, T. 2006. Hydraulic Response of Rubble Mound Breakwaters: scale effects - berm breakwaters. Ph.D.-thesis, Hydraulics & Coastal Engineering Laboratory, Department of Civil Engineering, Aalborg University, Aalborg. Series Paper, nr. 27.

Lykke Andersen, T., Van der Meer, J.W., Burcharth, H. F., Sigurdarson, S. 2012. Stability of Hardly Reshaping Berm Breakwaters. ICCE 2012: 33rd International Conference on Coastal Engineering. American Society of Civil Engineers.

Nørgaard, J.Q.H., Andersen, T.L., Burcharth, H.F. 2013. Wave loads on rubble mound breakwater crown walls in deep and shallow water wave conditions. Coastal Engineering, 80, pp. 137-147.

Pedersen, J. 1996. Wave Forces and Overtopping on Crown Walls of Rubble Mound Breakwaters. Ph.d. thesis, Series paper 12, ISBN 0909-4296, Hydraulics & Coastal Engineering Lab., Dept. of Civil Engineering, Aalborg University, Denmark.

Sigurdarson, S. and J. W. van der Meer. 2013. Design of berm breakwaters, recession, overtopping and reflection. Proc. ICE, Coasts, Marine Structures and Breakwaters 2013, Edinburgh, UK.

TAW. 2002. Technical Report: Wave Run-up and Wave Overtopping at Dikes, Technical Advisory Committee on Flood Defence, Delft.

Van der Meer, J.W. 1988. Rock Slopes and Gravel Beaches under wave Attack. PhD-thesis Delft University of Technology.

Van Gent, M.R.A., Smale, A.J. and Kuiper, C. 2003. Stability of rock slopes with shallow foreshores, ASCE, Proc. Coastal Structures 2003, Portland.

Van Gent, M.R.A., van den Boogaard, H.F.P., Pozueta, B, Medina, J.R. 2007. Neural network modelling of wave overtopping at coastal structures.

Van Gent, M.R.A. 2013. Rock Stability of Rubble Mound Breakwaters with a Berm, Coastal Engineering, Volume 78, August 2013, Pages 35-45, ISSN 0378-3839

Paper 1

Rock Armour Stability in Shallow Water Waves Conditions of Low Steepness
A New Stability Formula

Paper 2

Stability of Hardly Reshaping Berm Breakwaters Exposed to Long Waves

Paper 3

Overtopping on Rubble Mound Breakwaters for Low Steepness Waves in Deep and Depth Limited Conditions

Paper 4

Wave Loads on Rubble Mound Breakwater Crown Walls in Long Waves